

THE MID-INFRARED TULLY-FISHER RELATION: CALIBRATION OF THE SNIa SCALE AND H_0

JENNY G. SORCE¹, R. BRENT TULLY², AND HÉLÈNE M. COURTOIS^{1,2}

¹Université Claude Bernard Lyon I, Institut de Physique Nucleaire, Lyon, France and

²Institute for Astronomy, University of Hawaii, 2680 Woodlawn Drive, HI 96822, USA

Draft version August 17, 2012

ABSTRACT

This paper builds on a calibration of the SNIa absolute distance scale begun with a core of distances based on the correlation between galaxy rotation rates and optical I_C band photometry. This new work extends the calibration through the use of mid-infrared photometry acquired at $3.6\mu\text{m}$ with *Spitzer Space Telescope*. The great virtue of the satellite observations is constancy of the photometry at a level better than 1% across the sky. The new calibration is based on 39 individual galaxies and 8 clusters that have been the sites of well observed SNIa. The new $3.6\mu\text{m}$ calibration is not yet as extensively based as the I_C band calibration but is already sufficient to justify a preliminary report. Distances based on the mid-infrared photometry are 2% greater in the mean than reported at I_C band. This difference is only marginally significant. The I_C band result is confirmed with only a small adjustment. Incorporating a 1% decrease in the LMC distance, the present study indicates $H_0 = 75.2 \pm 3.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

Subject headings: cosmological parameters; galaxies: distances and redshifts; photometry: infrared

1. INTRODUCTION

Type Ia supernovae (SNIa) have remarkable properties such as their high luminosities ($10^9 L_\odot$) and their apparent homogeneous nature (Riess et al. 1995). Kowal (1968) established the first Hubble diagram that suggested SNIa could be used as extragalactic distance indicators. Two decades later, Phillips (1993) demonstrated the existence of a decline rate-absolute magnitude dependence for SNIa, validating that type Ia supernovae can act as standard candles. Work in subsequent years (Hamuy et al. 1995; Jha et al. 2007; Hicken et al. 2009; Amanullah et al. 2010) has produced alternate descriptions of the correlations between the intrinsic luminosities of SNIa and the shapes of their light curves.

The properties of SNIa can be used to determine distances to galaxies at many hundreds of megaparsecs. At such distances, object are expected to have recession velocities that individually differ from the mean by at most a few percent and collectively should define the cosmic expansion. Thanks to the great precision of SNIa distance estimates, high redshift SNIa revealed that the expansion of the universe is currently accelerating (Riess et al. 1998; Perlmutter et al. 1999). The SNIa method can provide the best estimate of the Hubble parameter once the zero point scale is set. Independent distances are needed to the hosts of low redshift SNIa (Riess et al. 2009, 2011; Folatelli et al. 2010) to establish the absolute scale.

Our collaboration has recently contributed to the establishment of the SNIa scale (Courtois & Tully 2012) primarily using constraints imposed by using distances acquired with the correlation between the luminosities and rotation rates of galaxies (Tully & Fisher 1977), the Tully-Fisher relation (TFR). Optical I_C band luminosities were used in that study. Now there is the opportunity to refine the calibration with the use of pho-

tometry at $3.6\mu\text{m}$ obtained with *Spitzer Space Telescope* (Werner et al. 2004). The great advantage with Spitzer observations is photometric integrity to better than 1% across the sky. Additional advantages are minimal obscuration either within hosts or from our Galaxy, magnitude measures approximating total magnitudes because of low backgrounds, and fluxes dominated by light from old stars which presumptively correlates with galaxy mass. By now, roughly 3000 galaxies have been observed with *Spitzer* and almost 1300 galaxies are being observed in the current cycle with our *Cosmic Flows with Spitzer* project (CFS¹). Already, 39 galaxies have been observed that have hosted SNIa and are appropriate for an application of the TFR methodology.

The present discussion will closely parallel the paper by Courtois & Tully (2012) with the important difference being the use of mid-infrared [3.6] photometry in place of optical I_C photometry. We begin with a brief summary of the data that are available on the hosts of SNIa galaxies and the treatment given to obtain distances using the TFR in the mid-infrared. Distance measurements obtained via the TFR are individually uncertain. Averaging over a cluster provides a more robust distance so we include clusters in our analysis. Distances determined with the TFR enable us to set a zero point for the SNIa distance scale. Consideration of a large sample of SNIa in the redshift range $0.03 < z < 0.5$ leads us to an estimate of the Hubble Constant.

2. DATA

Three parameters are needed to obtain distances with the TFR: a luminosity, a measure of rotation, and an inclination to account for projection effects. Our sample in this study is a subset of the sample used for the same purpose of a determination of SNIa host absolute luminosities by Courtois & Tully (2012). In the current paper we use the same information on rotation rates,

j.sorce@ipnl.in2p3.fr

¹ <http://adsabs.harvard.edu/abs/2011sptz.prop80072T>

from HI profile information, and inclinations, from optical band imaging. The difference in this work is the replacement of I_C luminosities with [3.6] luminosities from observations using *Spitzer Space Telescope* IRAC channel 1. Presently, not all the galaxies included in the I_C band study have been satisfactorily observed with *Spitzer*. We have retrieved data from the *Spitzer Heritage Archive* for 39 galaxies that have hosted SNIa from the list of 56 galaxies given by Courtois & Tully (2012). The archival material comes from the programs *Spitzer Infrared Nearby Galaxies Survey*, SINGS, (Dale et al. 2005, 2007), *Spitzer Survey of Stellar Structure in Galaxies*, S^4G , (Sheth et al. 2010), *Carnegie Hubble Program*, CHP, (Freedman et al. 2011), and our ongoing *Cosmic Flows with Spitzer* project, CFS.

Photometry for these galaxies is carried out using a *Spitzer*-adapted version of Archangel (Schombert & Smith 2012) described in Sorce et al. (2012a). Luminosity corrections for IRAC channel 1 flux measurements were described in detail in Sorce et al. (2012a). Briefly, observed total magnitudes, [3.6], must be corrected for extinction both within our Galaxy, $A_b^{[3.6]}$ (Schlegel et al. 1998), and within the hosts, $A_i^{[3.6]}$ (Tully et al. 1998), k -corrected, $A_k^{[3.6]}$ (Oke & Sandage 1968; Huang et al. 2007), and receive an aperture correction, $A_a^{[3.6]}$ (Reach et al. 2005). A fully corrected magnitude [3.6] b,i,k,a in the AB system for IRAC ch.1 *Spitzer* data is

$$[3.6]^{b,i,k,a} = [3.6] - A_b^{[3.6]} - A_i^{[3.6]} - A_k^{[3.6]} + A_a^{[3.6]} \quad (1)$$

3. HOST DISTANCES

Our calibration of the TFR at $3.6\mu\text{m}$ is described in Sorce et al. (2012b). The zero point is primarily set by Cepheids assuming a Large Magellanic Cloud (LMC) modulus 18.48 ± 0.03 (Freedman et al. 2012). The calibration used the correlation that assumes all errors are in the distance-independent line width parameter, the so-called ‘inverse’ fit. Corrections must be made to account for a small Malmquist bias effect with bias $b = -0.0065(\mu - 31)^2$ where μ is the distance modulus. Of greater importance is a color term. The calibration paper describes the tightening of the correlation that is provided by the adjustment to observed magnitude based on a color differential between the near-infrared I_C band and the mid-infrared [3.6] band

$$\Delta[3.6]^{color} = -0.36 - 0.47(I_C - [3.6]) \quad (2)$$

whence $C_{[3.6]} = [3.6]^{b,i,k,a} - \Delta[3.6]^{color}$. Absolute color adjusted magnitudes $M_{C_{[3.6]}}$ are given by the equation

$$M_{C_{[3.6]}} = -20.34 - 9.13(\log W_{mx}^i - 2.5) \quad (3)$$

where W_{mx}^i is the HI line width, de-projected from inclination i to edge-on, and adjusted to approximate twice the maximum rotation velocity of the galaxy (Courtois et al. 2011). The rms scatter about this mid-IR version of the TFR is ± 0.42 mag in the calibration sample. A distance modulus is given by $\mu^c = C_{[3.6]} - M_{C_{[3.6]}} - b$. These parameters are accumulated in Table 1 for 39 galaxies that have hosted SNIa and been observed with *Spitzer Space Telescope*.

Thirteen clusters were used to form the calibration template for the [3.6] band TFR (Sorce et al. 2012b) so there is a good distance determination for each of these clusters. Suitably observed SNIa have been observed in 8 of these clusters. Pertinent information is provided in Table 2. With the 2 nearest clusters (Virgo and Fornax) high quality distance measures are available from Cepheid and Surface Brightness Fluctuation observations and these measures contribute to (indeed, dominate) the values of the moduli in column 3 of the table. The averaging over multiple contributions follows Courtois & Tully (2012). When there were more than one SNIa observed per galaxy or cluster, or more than one observation per SNIa, we take averaged SNIa modulus estimates (Courtois & Tully 2012). The SNIa information is discussed in the next section.

4. SNIa ZERO POINT SCALE AND H_0

Courtois & Tully (2012) discuss the accumulation of a sample of SNIa from 5 sources (Prieto et al. 2006; Jha et al. 2007; Hicken et al. 2009; Folatelli et al. 2010; Amanullah et al. 2010) with scale shifts as appropriate to match the scale of the last of these sources, a compilation referred to as UNION2. Relevant distance moduli are gathered from these 5 sources and recorded in Table 2 with averaging in the case of clusters with multiple recorded SNIa events. Moduli drawn from Tables 1 and 2 are compared in Figure 1.

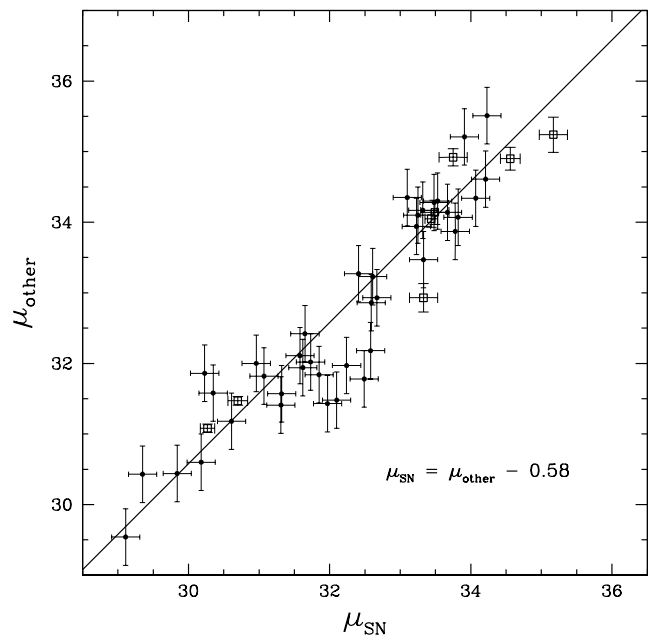


FIG. 1.— Comparison between moduli derived with SNIa and with ‘other’ methods: the TFR, with Cepheid and Surface Brightness Fluctuation supplements. The comparisons include 39 individual galaxies with TFR measurements (filled points) and 8 clusters (open squares). The straight line is a weighted fit to the 39 galaxies with TFR distances and 6 of the 8 clusters.

The straight line in this figure is a fit, assuming slope unity, to the 39 individual galaxies each with weight 1 and 6 clusters each with weight 9. The locations of two clusters are deviant (Centaurus at 5σ under the fit in Fig. 1 and A1367 at 3σ over the fit). These

two clusters were deviant and rejected from the optical SNIa calibration (Courtois & Tully 2012) and for consistency in the comparison are again rejected from the fit. The offset between the newly determined distance moduli (other) and the SNIa moduli on the UNION2 scale is $\mu_{\text{other}} - \mu_{\text{SN}} = 0.58$. The comparable fit with I_C band material was shown in Figure 5 of Courtois & Tully (2012). The offset in that earlier case was 0.56. The current calibration increases distances by 1% and reduce H_0 by 1%.

The galaxies observed to date with *Spitzer* are only a subset of those discussed in the I_C band calibration paper. It is instructive to compare results using only identical galaxies and clusters rather than using the ensemble of available samples as was done above. Figure 2 compares distance moduli measured alternatively with mid-IR [3.6] photometry with *Spitzer* and optical I_C photometry observed from the ground, using the same line width and inclination parameters. The comparison involves the 13 clusters used to establish the TFR template at I_C (Tully & Courtois 2012) and [3.6] (Sorce et al. 2012b) and the 39 individual galaxies that have hosted SNIa (Courtois & Tully (2012) and this paper). With the individual SNIa hosts there is a hint of an increase in the difference between moduli for the more distant cases but the trend is not statistically significant. No such trend is seen with the clusters. Overall the [3.6] moduli are greater than the I_C moduli by 0.02 ± 0.02 mag. The difference of 1% in distance is not statistically significant. It is to be noted, though, that the new mid-IR calibration is tied to a distance to the Large Magellanic Cloud that is 1% closer than previously assumed (Sorce et al. 2012b). With a common choice of LMC distance, the [3.6] band distances are 2% greater than those at I_C band.

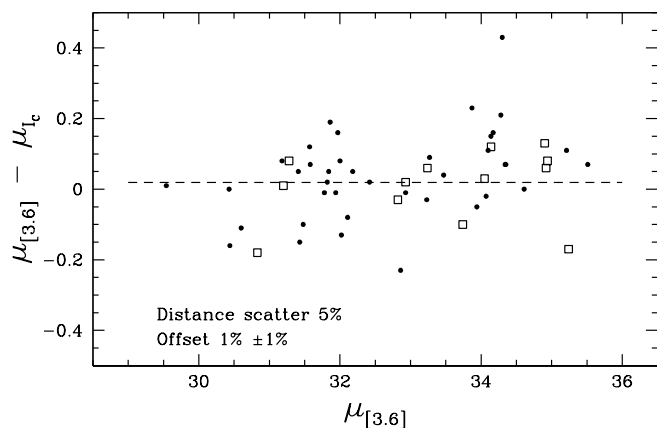


FIG. 2.— Differences in TFR distance moduli measured at [3.6] and at I_C plotted against the [3.6] moduli. Filled points: the 39 galaxies that have hosted SNIa; open squares: the 13 TFR template calibrator clusters.

The final calibration of the SNIa distance scale in the I_C band analysis of Courtois & Tully (2012) lead to the determination of the Hubble Constant shown in their Figure 8. It is based on a fit over the redshift range $0.03 < z < 0.5$ to the UNION2 sample (Amanullah et al. 2010), with cosmological parameters $\Omega_m = 0.27$, and $\Omega_\Lambda = 0.73$. The result obtained in that paper was

$H_0 = 75.9 \pm 3.8 \text{ km s}^{-1} \text{ Mpc}^{-1}$. In the present work, distances are decreased 1% due to a revised Large Magellanic Cloud modulus and increased 2% with the switch from optical I_C to mid-IR [3.6] magnitudes. The present calibration is in statistical agreement with the earlier work though formally gives a result 1% lower. An error budget was discussed by Courtois & Tully (2012). Uncertainties are reduced with this new work in two respects. First, there is increased confidence in the absolute scale set by the distance to the LMC (Freedman et al. 2012). Second, the mid-IR calibration of the TFR (Sorce et al. 2012b) removes latent concerns about possible photometric differences in different parts of the sky. These two improvements warrant a decrease in our error estimate from 5% to 4%. Our best estimate for the Hubble Constant is now $H_0 = 75.2 \pm 3.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

5. CONCLUSIONS

The new mid-infrared TFR calibration of the SNIa distance scale leads to a result for the Hubble Constant that is not significantly different from the earlier optical TFR calibration. The earlier calibration made use of a considerably larger collection of material. Besides using over 50% more individual TFR galaxies, it gave consideration to 61 groups or clusters hosting SNIa with distances not only from the TFR but also with Cepheid, surface brightness fluctuation, and fundamental plane measurements. Nevertheless we contend that the present confirming work has value because it puts to rest a concern with the optical study. The optical photometry was acquired by a diverse community of observers on several telescopes with a variety of detectors and filters and subject to the vagaries associated with ground-based observations. This new mid-IR photometry is being acquired with a single observing configuration in space advertising photometric consistency across the sky to better than 1%. In the fullness of time it can be anticipated that the mid-IR calibration of the distance scale will be made more robust with linkages to SNIa involving several hundred galaxies. The paper describing the calibration of the mid-IR TFR had already lead to a preliminary determine of the Hubble Constant of $H_0 = 74 \pm 4 \text{ km s}^{-1} \text{ Mpc}^{-1}$ (Sorce et al. 2012b). The present study extends the calibration to distances where peculiar velocities should have negligible impact and we find $H_0 = 75.2 \pm 3.0 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

We especially thank our *Cosmic Flows with Spitzer* collaborators Wendy Freedman, Tom Jarrett, Barry Madore, Eric Persson, Mark Seibert, and Ed Shaya although most of the data used in this paper comes from the *Spitzer* archive. We are indebted to James Shombert for the development and support of the Archangel photometry package. We thank Kartik Sheth for discussions regarding *Spitzer* photometry. NASA through the *Spitzer Science Center* provides support for *Cosmic Flows with Spitzer* cycle 8 program 80072. RBT receives support for aspects of this program from the US National Science Foundation with award AST-0908846.

TABLE 1
PROPERTIES OF INDIVIDUAL SNIa GALAXIES

Name ^a	PGC ^b	SNIa ^c	V_{CMB} ^d	W_{mx}^i ^e	$[3.6]^{b,i,k,a}$ ^f	$C_{[3.6]}^g$	$M_{C_{[3.6]}}^h$	μ_{TF}^i	μ_{SN}^j
UGC00646	3773	1998ef	5011	389	12.89	12.88	-21.16	34.10	33.25
PGC005341	5341	1998dm	1663	236	12.91	12.79	-19.18	31.97	32.24
NGC0673	6624	1996bo	4898	445	12.04	12.19	-21.69	33.94	33.23
NGC0958	9560	2005A	5501	584	11.09	11.24	-22.77	34.07	33.82
ESO300-9	11606	1992bc	5918	323	14.69	14.67	-20.42	35.21	33.91
NGC1148	13727	2001el	1092	386	10.05	10.05	-21.13	31.18	30.61
UGC03329	17509	1999ek	5277	525	12.13	11.89	-22.35	34.30	33.53
UGC03375	18089	2011gc	5792	535	11.82	11.78	-22.42	34.28	33.48
PGC018373	18373	2003kf	2295	234	12.72	12.69	-19.15	31.84	31.85
UGC03432	18747	1996bv	5015	289	14.20	14.12	-19.98	34.17	33.32
UGC03576	19788	1998ec	6013	393	13.03	13.07	-21.20	34.34	34.07
UGC03370	20513	2000fa	6525	371	13.48	13.56	-20.97	34.61	34.21
UGC03845	21020	1997do	3136	257	13.35	13.39	-19.52	32.93	32.67
NGC2841	26512	1999by	804	650	8.68	8.66	-23.20	31.86	30.23
NGC3021	28357	1995al	1797	303	11.68	11.84	-20.17	32.02	31.73
NGC3294	31428	1992G	1831	431	10.77	10.84	-21.57	32.42	31.65
NGC3368	32192	1998bu	1231	428	8.80	8.89	-21.54	30.43	29.35
NGC3370	32207	1994ae	1609	312	11.68	11.81	-20.29	32.11	31.58
NGC3627	34695	1989b	1061	385	8.33	8.40	-21.12	29.54	29.11
NGC3663	35006	2006ax	5396	443	12.44	12.41	-21.68	34.14	33.67
NGC3672	35088	2007bm	2223	399	10.59	10.68	-21.26	31.94	31.62
NGC4501	41517	1999cl	2601	570	8.84	8.90	-22.68	31.58	30.35
NGC4527	41789	1991T	2072	362	9.34	9.56	-20.88	30.44	29.84
NGC4536	41823	1981B	2144	341	9.81	9.96	-20.64	30.60	30.18
NGC4639	42741	1990N	1308	336	11.18	11.23	-20.58	31.82	31.07
NGC4680	43118	1997bp	2824	237	12.09	12.23	-19.20	31.43	31.97
NGC4679	43170	2001cz	4935	427	11.83	11.90	-21.53	33.47	33.33
NGC5005	45749	1996ai	1178	601	9.05	9.11	-22.89	32.00	30.96
ESO576-040	46574	1997br	2385	170	13.82	13.69	-17.88	31.57	31.32
PGC47514	47514	2007ca	4517	285	14.03	13.89	-19.93	33.87	33.78
NGC5584	51344	2007af	1890	267	11.75	11.74	-19.67	31.41	31.31
IC1151	56537	1991M	2274	242	12.91	12.88	-19.28	32.18	32.58
NGC6063	57205	1999ac	2950	308	13.06	13.01	-20.24	33.27	32.41
UGC10738	59769	2001cp	6726	585	12.52	12.61	-22.78	35.51	34.23
UGC10743	59782	2002er	2574	206	12.74	12.83	-18.64	31.48	32.10
NGC6962	65375	2002ha	3936	633	11.11	11.19	-23.09	34.35	33.10
IC5179	68455	1999ee	3158	444	10.86	11.15	-21.69	32.86	32.59
NGC7329	69453	2006bh	3143	461	11.24	11.36	-21.83	33.23	32.61
NGC7448	70213	1997dt	1838	316	11.37	11.44	-20.34	31.78	32.49

^aCommon name^bPGC name^cSNIa identification^dMean velocity of host galaxy with respect to the CMB, km/s^eCorrected rotation rate parameter corresponding to twice maximum velocity, km/s^fCorrected 3.6 μ m magnitude in the AB system, mag^gColor adjusted magnitude, mag^hAbsolute color adjusted magnitude, magⁱTFR distance modulus corrected for bias, mag^jSNIa distance modulus, mag

TABLE 2
PROPERTIES OF CLUSTERS WITH SNIa

Cluster ^a	V_{CMB} ^b	μ_{other} ^c	No. CFS ^d	μ_{SN} ^e	SNIa names ^f
Virgo	1410	31.08 ± 0.06	24	30.27 ± 0.10	1991bg, 1994D, 1999cl, 2006X
Fornax	1484	31.47 ± 0.06	15	30.70 ± 0.14	1980N, 1992A
Cen30	3679	32.93 ± 0.20	11	33.33 ± 0.20	2001cz
Pisces	4779	34.05 ± 0.11	23	33.44 ± 0.09	1998ef, 1999ej, 2000dk, 2001en, 2006td
Cancer	4940	34.14 ± 0.13	11	33.49 ± 0.20	1999aa
Coma	7194	34.90 ± 0.13	16	34.56 ± 0.14	2006cg, 2007bz
A1367	6923	34.92 ± 0.14	19	33.75 ± 0.20	2007ci
A2634/66	8381	35.24 ± 0.13	18	35.17 ± 0.20	1997dg

^aCluster name

^bMean velocity of the cluster with respect to the CMB, km/s

^cTFR distance modulus corrected for bias (Virgo and Fornax are special cases discussed in text), mag

^dNumber of galaxies used in the TFR calibration

^eSNIa distance modulus, mag

^fSNIa identifications

REFERENCES

- Amanullah, R., Lidman, C., Rubin, D., Aldering, G., Astier, P., Barbary, K., Burns, M. S., Conley, A., Dawson, K. S., Deustua, S. E., Doi, M., Fabbro, S., Faccioli, L., Fakhouri, H. K., Folatelli, G., Fruchter, A. S., Furusawa, H., Garavini, G., Goldhaber, G., Goobar, A., Groom, D. E., Hook, I., Howell, D. A., Kashikawa, N., Kim, A. G., Knop, R. A., Kowalski, M., Linder, E., Meyers, J., Morokuma, T., Nobili, S., Nordin, J., Nugent, P. E., Östman, L., Pain, R., Panagia, N., Perlmutter, S., Raux, J., Ruiz-Lapuente, P., Spadafora, A. L., Strovink, M., Suzuki, N., Wang, L., Wood-Vasey, W. M., Yasuda, N., & Supernova Cosmology Project. 2010, *ApJ*, 716, 712
- Courtois, H. M. & Tully, R. B. 2012, *ApJ*, 749, 174
- Courtois, H. M., Tully, R. B., Makarov, D. I., Mitronova, S., Koribalski, B., Karachentsev, I. D., & Fisher, J. R. 2011, *MNRAS*, 414, 2005
- Dale, D. A., Bendo, G. J., Engelbracht, C. W., Gordon, K. D., Regan, M. W., Armus, L., Cannon, J. M., Calzetti, D., Draine, B. T., Helou, G., Joseph, R. D., Kennicutt, R. C., Li, A., Murphy, E. J., Roussel, H., Walter, F., Hanson, H. M., Hollenbach, D. J., Jarrett, T. H., Kewley, L. J., Lamanna, C. A., Leitherer, C., Meyer, M. J., Rieke, G. H., Rieke, M. J., Sheth, K., Smith, J. D. T., & Thornley, M. D. 2005, *ApJ*, 633, 857
- Dale, D. A., Gil de Paz, A., Gordon, K. D., Hanson, H. M., Armus, L., Bendo, G. J., Bianchi, L., Block, M., Boissier, S., Boselli, A., Buckalew, B. A., Buat, V., Burgarella, D., Calzetti, D., Cannon, J. M., Engelbracht, C. W., Helou, G., Hollenbach, D. J., Jarrett, T. H., Kennicutt, R. C., Leitherer, C., Li, A., Madore, B. F., Martin, D. C., Meyer, M. J., Murphy, E. J., Regan, M. W., Roussel, H., Smith, J. D. T., Sosey, M. L., Thilker, D. A., & Walter, F. 2007, *ApJ*, 655, 863
- Folatelli, G., Phillips, M. M., Burns, C. R., Contreras, C., Hamuy, M., Freedman, W. L., Persson, S. E., Stritzinger, M., Suntzeff, N. B., Krisciunas, K., Boldt, L., González, S., Krzeminski, W., Morrell, N., Roth, M., Salgado, F., Madore, B. F., Murphy, D., Wyatt, P., Li, W., Filippenko, A. V., & Miller, N. 2010, *AJ*, 139, 120
- Freedman, W. L., Madore, B. F., Scowcroft, V., Monson, A., Persson, S. E., Seibert, M., Rigby, J. R., Sturch, L., & Stetson, P. 2011, *AJ*, 142, 192
- Hamuy, M., Phillips, M. M., Maza, J., Suntzeff, N. B., Schommer, R. A., & Aviles, R. 1995, *AJ*, 109, 1
- Hicken, M., Wood-Vasey, W. M., Blondin, S., Challis, P., Jha, S., Kelly, P. L., Rest, A., & Kirshner, R. P. 2009, *ApJ*, 700, 1097
- Huang, J.-S., Ashby, M. L. N., Barmby, P., Brodwin, M., Brown, M. J. I., Caldwell, N., Cool, R. J., Eisenhardt, P., Eisenstein, D., Fazio, G. G., Le Floc'h, E., Green, P., Kochanek, C. S., Lu, N., Pahre, M. A., Rigopoulou, D., Rosenberg, J. L., Smith, H. A., Wang, Z., Willmer, C. N. A., & Willner, S. P. 2007, *ApJ*, 664, 840
- Jha, S., Riess, A. G., & Kirshner, R. P. 2007, *ApJ*, 659, 122
- Kowal, C. T. 1968, *AJ*, 73, 1021
- Oke, J. B. & Sandage, A. 1968, *ApJ*, 154, 21
- Perlmutter, S., Aldering, G., Goldhaber, G., Knop, R. A., Nugent, P., Castro, P. G., Deustua, S., Fabbro, S., Goobar, A., Groom, D. E., Hook, I. M., Kim, A. G., Kim, M. Y., Lee, J. C., Nunes, N. J., Pain, R., Pennypacker, C. R., Quimby, R., Lidman, C., Ellis, R. S., Irwin, M., McMahon, R. G., Ruiz-Lapuente, P., Walton, N., Schaefer, B., Boyle, B. J., Filippenko, A. V., Matheson, T., Fruchter, A. S., Panagia, N., Newberg, H. J. M., Couch, W. J., & Supernova Cosmology Project. 1999, *ApJ*, 517, 565
- Phillips, M. M. 1993, *ApJ*, 413, L105
- Prieto, J. L., Rest, A., & Suntzeff, N. B. 2006, *ApJ*, 647, 501
- Reach, W. T., Megeath, S. T., Cohen, M., Hora, J., Carey, S., Surace, J., Willner, S. P., Barmby, P., Wilson, G., Glaccum, W., Lowrance, P., Marengo, M., & Fazio, G. G. 2005, *PASP*, 117, 978
- Riess, A. G., Filippenko, A. V., Challis, P., Clocchiatti, A., Diercks, A., Garnavich, P. M., Gilliland, R. L., Hogan, C. J., Jha, S., Kirshner, R. P., Leibundgut, B., Phillips, M. M., Reiss, D., Schmidt, B. P., Schommer, R. A., Smith, R. C., Spyromilio, J., Stubbs, C., Suntzeff, N. B., & Tonry, J. 1998, *AJ*, 116, 1009
- Riess, A. G., Macri, L., Casertano, S., Lampeitl, H., Ferguson, H. C., Filippenko, A. V., Jha, S. W., Li, W., & Chornock, R. 2011, *ApJ*, 730, 119
- Riess, A. G., Macri, L., Casertano, S., Sosey, M., Lampeitl, H., Ferguson, H. C., Filippenko, A. V., Jha, S. W., Li, W., Chornock, R., & Sarkar, D. 2009, *ApJ*, 699, 539
- Riess, A. G., Press, W. H., & Kirshner, R. P. 1995, *ApJ*, 438, L17
- Schlegel, D. J., Finkbeiner, D. P., & Davis, M. 1998, *ApJ*, 500, 525
- Schombert, J. & Smith, A. K. 2012, *PASA*, 29, 174
- Sheth, K., Regan, M., Hinz, J. L., Gil de Paz, A., Menéndez-Delmestre, K., Muñoz-Mateos, J.-C., Seibert, M., Kim, T., Laurikainen, E., Salo, H., Gadotti, D. A., Laine, J., Mizusawa, T., Armus, L., Athanassoula, E., Bosma, A., Buta, R. J., Capak, P., Jarrett, T. H., Elmegreen, D. M., Elmegreen, B. G., Knapen, J. H., Koda, J., Helou, G., Ho, L. C., Madore, B. F., Masters, K. L., Mobasher, B., Ogle, P., Peng, C. Y., Schinnerer, E., Surace, J. A., Zaritsky, D., Comerón, S., de Swardt, B., Meidt, S. E., Kasliwal, M., & Aravena, M. 2010, *PASP*, 122, 1397
- Sorce, J., Courtois, H. M., & Tully, R. B. 2012a, *ArXiv e-prints*
- Sorce, J., Courtois, H. M., Tully, R. B., Seibert, M., Scowcroft, V., Freedman, W. L., Madore, B. F., Persson, S. E., Monson, A., & Rigby, J. 2012b, *ArXiv e-prints*
- Tully, R. B. & Courtois, H. M. 2012, *ApJ*, 749, 78
- Tully, R. B. & Fisher, J. R. 1977, *A&A*, 54, 661
- Tully, R. B., Pierce, M. J., Huang, J.-S., Saunders, W., Verheijen, M. A. W., & Witchalls, P. L. 1998, *AJ*, 115, 2264
- Werner, M. W., Roellig, T. L., Low, F. J., Rieke, G. H., Rieke, M., Hoffmann, W. F., Young, E., Houck, J. R., Brandt, B., Fazio, G. G., Hora, J. L., Gehrz, R. D., Helou, G., Soifer, B. T., Stauffer, J., Keene, J., Eisenhardt, P., Gallagher, D., Gautier, T. N., Irace, W., Lawrence, C. R., Simmons, L., Van Cleve, J. E., Jura, M., Wright, E. L., & Cruikshank, D. P. 2004, *ApJS*, 154, 1